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H2A AGH
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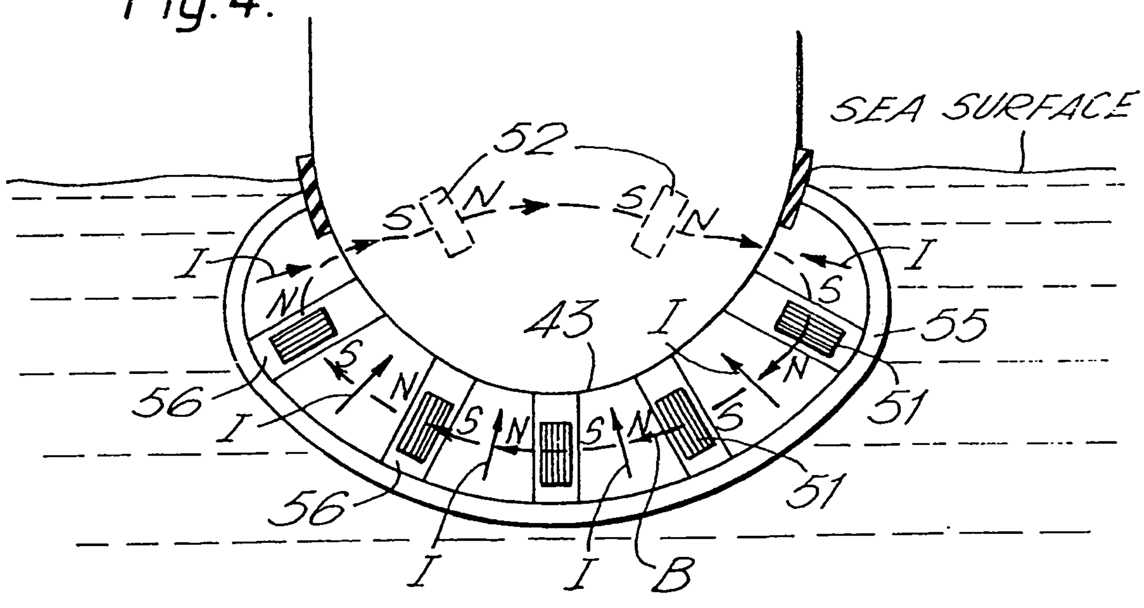
(54) Magnetohydrodynamic propulsion arrangements for marine vessels

(57) An MHD (magnetohydrodynamic) propulsion arrangement for ships or other marine vessels, in which the magnetic field B is trapped in a closed path by solenoids 51, 52 and, optionally, magnetic shunts. The interacting current I is then passed radially through this path between electrodes at least the outer one of which extends around a major part of the magnetic path. The flux and currnet paths are then oriented, by virtue of their mounting on the ship, to produce a force along the ship axis. A highly efficient high speed propulsion system can thus be produced.

Fig. 4.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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Fig.1.

PRIOR ART

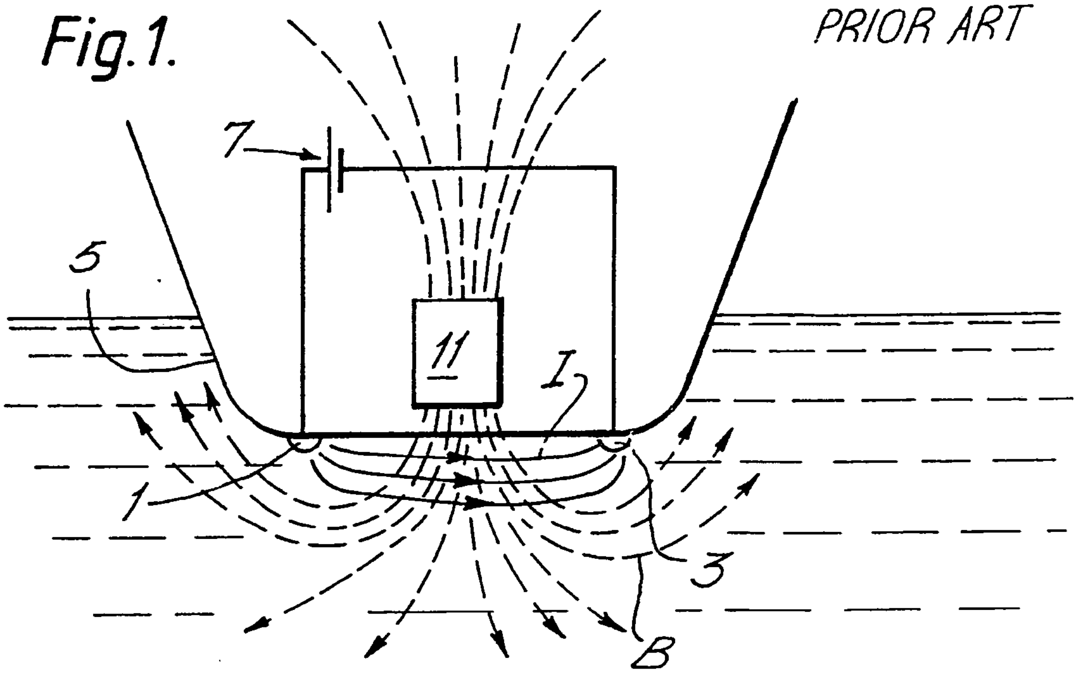

Fig.2.

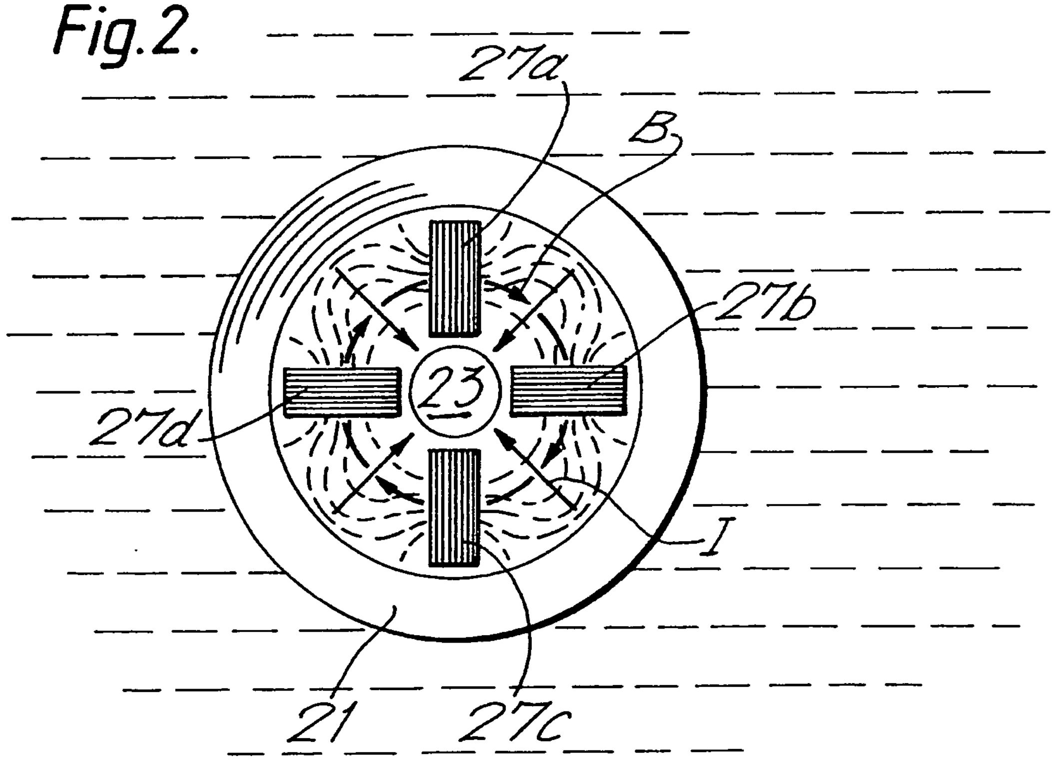

Fig.3.

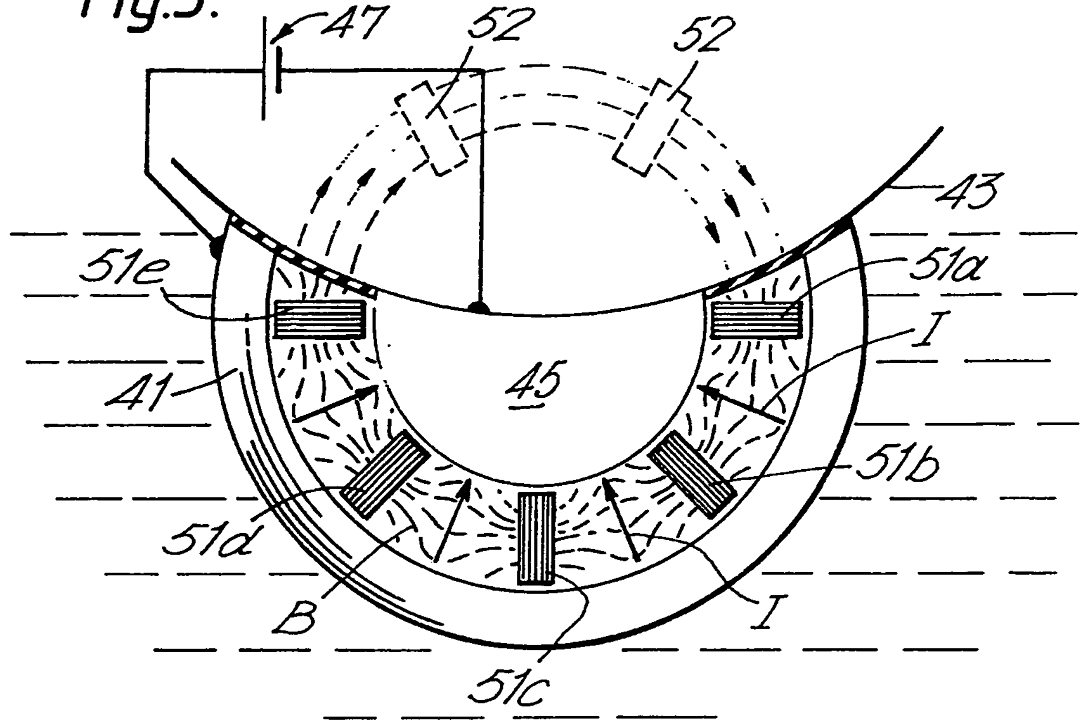
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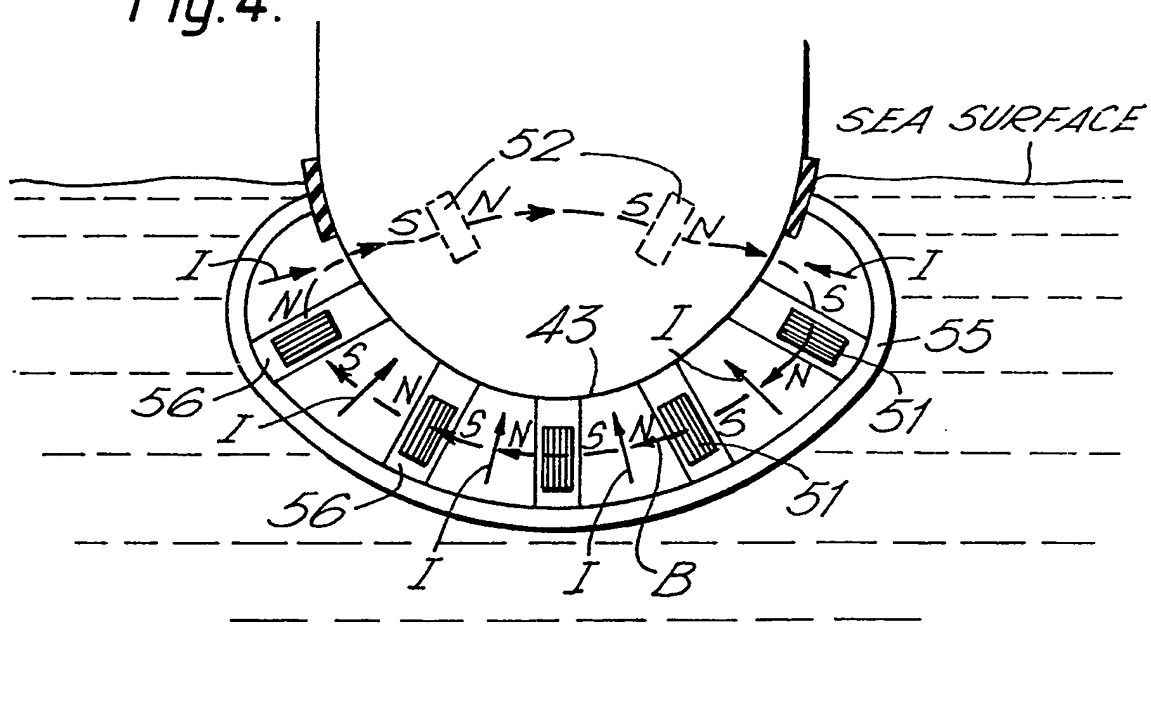
Fig.4.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Magnetohydrodynamic Propulsion Arrangements

This invention relates to magnetohydrodynamic (MHD) propulsion arrangements.

Such an arrangement, shown schematically in Figure 1 of the accompanying drawings, is known for propelling a boat through water. This arrangement comprises electrodes 1 and 3, fixed to the hull 5 at positions spaced across it. The electrodes are, of course, insulated from the hull. A D.C. source 7 drives a current I through the water between the electrodes. A solenoid 11 is mounted within the hull so as to create a vertical magnetic field B through the current path. The interaction between the magnetic field B and the current I produces longitudinal force on the water, the reaction to which propels the boat.

However, this arrangement is inefficient for a number of reasons.

First there is a heat loss in passing current through the sea, this loss being proportional to the integral over the sea of the square of the current density.

The electrical losses in producing the magnetic field are relatively small and will be very small when superconducting solenoids become available. Thus the main loss term is due to the sea current.

For the simple system of Figure 1, both the field strength and the current density fall off as the cube of the distance from the solenoid and the electrodes respectively. Thus their spatial variation is similar and consequently the two are proportional. The force, which is proportional to the product of field and current density, thus varies with the square of the current density and therefore with the local electrical loss. It appears therefore that large force goes hand in hand with large losses and the resulting inefficiency is inherent.

Again, the current at any point can be represented by a vector, which can be resolved into components one at right angles and one parallel to the magnetic field. The parallel component causes a heating loss without thrust generation. Thus, for efficiency, the current should everywhere be orthogonal to the magnetic field. This is difficult to arrange, particularly for a surface vessel, because magnetic field is not affected by the sea surface, but the surface is a barrier that the current cannot pass. In addition, the extent of the current and field away from the ship makes control of their angular relationship difficult or impossible.

The simple system of Figure 1 has two electrodes and one dipole solenoid and, as mentioned above, the effect of each falls off as $1/\text{distance}^3$. The product (the force) therefore falls off as $1/\text{distance}^6$. It is easy to see that most force is generated near the magnetic poles. Thus, if the field near one pole is inside the vessel, as in Figure 1, and cannot be utilised, current density must be increased to produce the required force, so increasing the above energy losses.

It is an object of the present invention to provide an MHD propulsion arrangement with efficiency significantly improved over that of the simple arrangement of Figure 1.

According to the present invention there is provided a magnetohydrodynamic propulsion arrangement comprising means for generating a magnetic flux in a path which extends between opposed electrodes at least one of which extends along a major part of the flux path, the electrodes being of such form and disposition as to

provide minimal obstruction to the flow of liquid therebetween in a direction transverse to the flux path, the arrangement being such that when the electrodes are immersed in a conductive liquid in the presence of said magnetic flux and an electric current is passed through the conductive liquid between the electrodes, a propulsive force is produced in a direction transverse to the flux path and to the current path.

The electrodes preferably comprise a central localised electrode and an outer electrode surrounding the central electrode.

The central electrode may be in the form of a disc and the outer electrode in the form of an annulus.

Alternatively, the central electrode may be in the form of a rod and the outer electrode in the form of a tube.

The electrodes preferably extend in the direction of liquid flow, and the outer electrode may be of arcuate cross-section transverse to this direction.

The means for generating a magnetic flux preferably comprises a plurality of solenoids distributed between the electrodes and along the flux path.

The propulsion arrangement may be mounted on a ship at the rear end of its hull with the direction of liquid flow aligned with the ship's longitudinal axis. In this case the outer electrode, the hull and the inner electrode may form a duct for the passage of water, the reaction from which provides a propulsive force on the ship. The inner electrode may be constituted by the hull of the ship or, alternatively, the inner electrode may comprise a conductive surface or surfaces fixed to the hull.

Several MHD propulsion arrangements in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a schematic diagram of the known MHD propulsion arrangement described above; and

Figures 2, 3 and 4 are end views of various arrangements according to the invention.

MHD has been known for years but has remained an academic curiosity (apart from specialised applications such as pumping liquid metals), for the simple reason that systems proposed hitherto for application to a ship, such as that of Figure 1, would give the ship an impractically low top speed. With the present invention, particularly if taking advantage of developments in superconducting materials for making high power solenoids, MHD for ship propulsion becomes a practical proposition. MHD ship propulsion must ideally offer the following:

(a) reasonable efficiency, preferably better than propeller propulsion;

(b) no serious operational problems.

The simple system shown in Figure 1 is inefficient and has operational problems.

Efficiency is maximised by minimising losses. We can define efficiency N as

$$N = \frac{\text{mechanical power out}}{\text{electrical power in}} \times \frac{\text{speed of vessel x drag}}{\text{mechanical power out}}$$

i.e.

$$N = N_A \times N_p$$

Where N_A is the efficiency of conversion of electrical power to mechanical power and N_p is propulsive efficiency.

The preferred embodiments of the invention to be described, minimise electrical losses, making N_A large, and also give high propulsive efficiency N_p.

Considering the drag factor, referred to above in the definition of efficiency, drag is a reaction between the ship and the water, and can be divided into two parts:

(a) wave drag and

(b) viscous and turbulent drag arising in the wake of the vessel.

Wave drag is negligible compared with wake drag for very large vessels and also for submerged vessels at a depth not less than several body diameters.

The wake consists of fluid moving relative to the surrounding sea. For efficient self-propulsion at a steady speed, the propulsor must produce an equal and opposite change of momentum to that imposed on the water by the drag effect, so that the net wake momentum, including propulsor efflux, is zero. However, if there is movement in this combined wake, then kinetic energy is being left in the wake, and this is a loss. For maximum propulsive efficiency we desire to minimise this wake kinetic energy.

Wake kinetic energy is minimised if the propulsor, mounted at the rear of the vessel, ingests the wake and reaccelerates it to leave it substantially at rest relative to the surrounding sea.

Operational problems with MHD propulsion systems may arise from both the stray currents and the stray magnetic fields involved.

Considering first the current factor, if a current is passed through water between two electrodes, and a conducting object is placed in the water, then some of the current will pass through the conducting object. If the object is metal (e.g. steel) then this passage of current will cause local etching away of the steel. If the electrodes are mounted as in Figure 1, on a metal ship, then the ship may develop leaks in a short time. In principle the hull can be insulated, but any surface damage can allow the sea to reach the hull. If the hull is limited to materials such as wood or fibreglass to overcome this problem then certain designs requiring the availability of a conductive hull are precluded.

In at least one inventive arrangement described herein, the current is concentrated locally and, as will be seen, is <u>radial</u> with respect to the transverse curve of the hull. The voltage gradient in the sea along the hull surface (i.e. transversely) will therefore be very small. Thus, any corrosion problem is much reduced. If still significant, the electrical power required to apply a voltage bias to the hull, and thus prevent corrosion, would be low enough to be acceptable.

Considering now the stray field factor as a cause of operational problems, such problems have already been reported with magnetically levitated trains, such as the stopping of passengers' watches. There is also concern that heart pacemakers may be affected. The stray fields resulting from ship propulsion with the system of Figure 1 would be orders of magnitude greater than those associated with levitated trains. Potential problems internal to the ship include:

(a) effect on watches

(b) effect on pacemakers

(c) physiological effects on the crew. A sufficiently high magnetic field could damage health by several physiological effects. Although such a field would need to be very intense it does not appear to be known whether MHD involves fields of this intensity.

(d) ships electrical equipment would be affected. In particular, transformers might not operate correctly.

(e) the handling of steel objects would be difficult, e.g. tools, doors on the ship.

Potential problems external to the ship include:

(a) it might be difficult to control berthing next to a steel ship. To avoid accidents, it would probably be necessary to use an auxiliary propulsion system in harbour.

(b) the stray magnetic field would upset compass corrections in surrounding vessels.

(c) ferrous debris might be picked up from the bottom in shallow water.

It appears that all the above problems become insignificant in preferred embodiments according to the present invention because of the reduction achieved in the stray field.

Referring now to Figure 2 of the accompanying drawings, the first MHD propulsion arrangement (engine), shown immersed in water, comprises an electrode in the form of an annulus or short cylinder 21, at the centre of which is disposed an opposing, localised, electrode in the form of a short rod or disc 23. Increasing the axial

length of the electrodes, and thus the area, reduces the current density, and thus the heating losses. However, increasing the electrode area increases the skin friction and drag. In practice the length would be chosen to minimise the sum of the heating and friction losses.

A D.C. source (not shown) drives a current radially through the water between the electrodes 21,23 as indicated by the arrows I. A magnetic flux source in the form of solenoids 27a - 27d also supplied with a direct current and positioned so as to form distributed sections of an annular or doughnut shaped coil surrounding the electrode 23 thus embrace and define a compact, low reluctance flux path B around the electrode 23. This flux path B is of very low reluctance compared to the long and ill-defined path obtaining in the Figure 1 arrangement. The field strength in path B is therefore much increased and the resulting force correspondingly greater. In addition, a major proportion of the magnetic field path B traverses the current path I producing an equal force on the water as in the known arrangement of Figure 1 but with a much reduced current. In practice the electrodes 21, 23 and the solenoids 27 will be fixed to a ship's or submarine's hull towards the rear of the vessel to embrace and ingest the wake as explained above.

Where the electrodes 21,23 are of considerable axial extent, i.e. in the form of a co-axial tube and rod respectively, the solenoids, 27a-27d as described above, could each consist of a single coil having turns which extend substantially along the entire length of the electrodes. Alternatively, it may be more convenient to replace each single coil with a number of electrically connected smaller coils spaced apart along the length of the electrodes, the coils of each solenoid being co-planar in a plane containing the axis of the rod 23, and, in combination, providing essentially the same magnetic flux as the single coil arrangement. The propulsive force generated by these arrangements is increased according to the increased interaction of magnetic flux and electric current.

Referring to Figure 3, the second MHD propulsion arrangement comprises a positive electrode in the form of an axially elongate member 41 of arcuate cross-section fixed along the length of a ship's hull 43. A negative electrode in the form of a part cylindrical hollow or solid member 45 is also fixed along the length of the hull. At least one of the electrodes is insulated from the hull. A D.C. source 47 drives a current radially through the water between the electrodes 41, 45, as indicated by the arrows I. A magnetic flux source, in the form of solenoids 51a - 51e also supplied with a direct current, are positioned so as to form distributed sections of a part of an annular or doughnut shaped coil surrounding the electrode 45 and thus embracing a single flux path around the electrode 45.

Additional solenoids 52 within the hull constrain the flux path and maintain low reluctance. Alternatively, a substantial high permeability magnetic shunt within the hull may be used to close the flux path.

Figure 4 shows a modification of the arrangement of Figure 3 in which the cylindrical electrode is, in effect, opened out to conform to the transverse section of the hull. The inner electrode may then be constituted by the ship's hull 43 itself, or by an electrode conforming to and fixed to the hull, whether insulated from the hull or not. Such an electrode may be metallic or of carbon. Where the hull itself is used as the inner electrode, the outer electrode 55 is insulated from the hull over a sufficient extent to prevent shorting of the current. Again, internal solenoids 52, or a high permeability bridge, are used to close the flux path if the hull structure is not itself a sufficient shunt. An advantage of the arrangements shown in Figures 3 and 4 is that the magnetic flux path is effectively wholly contained within the MHD engine and the ship's hull, and a major part of the flux path extends along the outer electrode. This ensures a high efficiency in the interaction between the magnetic flux and the electric current flow between the electrodes.

The design of Figure 4 ensures that the major part of the ship's wake is ingested by the propulsion arrangement in accordance with the design requirements outlined above, thus providing maximum propulsion efficiency.

For an axi-symmetric body, e.g. a torpedo, the wake is axi-symmetric. The fluid closest to the body surface will have acquired the greatest velocity from the drag effect. If the water is accelerated back to the stationary condition it will have lost most energy and thus will have provided most work for the propulsor to do and thus most propulsion force. The radial current flow automatically gives increased current density and thus increased force near the body. The detail match of the force generation to the wake velocity profile can be refined by varying the axial extent of each solenoid as a function of radius.

A single rotation propulsor (i.e. a propeller) leaves angular momentum in the water, with an associated kinetic energy loss. This loss occurs even in a wake adapted propeller. Thus, the described MHD systems offer better propulsive efficiency than a single propeller.

For a surface vessel, the design of the propeller is a compromise. If the propeller diameter is too small, the propeller does not ingest a substantial proportion of the wake. If the propeller is too large, the top blade tip is shallow and will cavitate, while the bottom blade tip may suffer damage in shallow water. Also the flow round the rear of a typical ship is not the clean uniform flow desirable if high propeller efficiency is to be obtained. In the MHD design force is produced as a body force on the water rather than by pressure differences across a propeller blade, cavitation is much less likely.

The effect of the MHD design on drag reduction may be seen as follows:

(1) Flow separates at the rear of a typical ship, giving high drag.

(2) Consider a ship with a short taper (large included angle) at the rear. The flow will still separate because of the pressure field at the rear of the ship.

(3) Now add an MHD propulsor such as that of Figure 4. This generates a pressure field, purely by its physical presence, which can be changed by altering the shape of the outer electrode, which acts as a wing or aerofoil.

(4) The design may be such that the new pressure field does not cause flow separation. Thus the optimised ship with optimised MHD propulsor has both low drag and efficient propulsion.

(5) The effect discussed above is known and used for axi-symmetric bodies (e.g. submarines) driven by propeller (which forms an axi-symmetric actuator disc). The application to reducing ship drag is new, because the MHD propulsor can be shaped to conform to the ship surface whereas a propeller cannot.

The solenoids in the above arrangements are enclosed in non-magnetic, non-conducting housings to form structural fins supporting the outer electrode. The rear ends of the electrodes and (solenoid) fins may then be used for mounting control surfaces, rudders, etc. Such mounting would give effective control even at low forward speed.

In the above described arrangements, the bulk of the magnetic flux from a north pole of a solenoid passes through the water into the south pole of an adjacent solenoid. Thus all poles of each solenoid are fully utilised (for the axi-symmetric case). What matters for efficient propulsion is the field strength in the water. The proposed configurations, by giving a low reluctance path between pole faces of opposite polarity, give a very high field strength in the water, allowing current to be kept to a minimum for a given force.

With regard to the operational problems resulting from the spreading out of both the current field and the magnetic field in the Figure 1 arrangement the invention gives very rapid reduction of both current density and magnetic field strength with distance (i.e. of the order of $1/\text{distance}^n$ where n depends on the number of solenoids and electrodes but could typically be 9 or greater). This local concentration of both current and magnetic field minimises the operational problems described above resulting from both stray current and stray magnetic field.

The high magnetic fields, necessary for effective MHD, cause large forces. The invention provides a geometry for which these large forces are localised in the propulsor system, and cause relatively low stresses.

Other advantages are:

(a) the propulsor geometry gives low drag;

(b) the propulsor geometry allows shallow operation without cavitation.

It will be appreciated that if the windings of the solenoids 27 (Figure 2), 51 (Figures 3 and 4) were made of a superconducting material, the efficiency would be greatly increased.

It will be noted that the direct current applied to the electrodes and the solenoids above could be replaced by a.c. provided that the respective alternating currents were arranged to be synchronous so that the force produced on the water remained constant in direction.

It will be noted that the above described propulsion arrangements could be employed with different (conducting) liquids in a different application where the liquid were required to be propelled.

It will also be appreciated that the physical shape and disposition of the electrodes 21,23 (Figure 2), 41,45 (Figure 3) and 55 (Figure 4) need not be as described above but could be of any physical shape and disposition such that at least one of the electrodes extends parallel to, or at least along, a major part (i.e. at least a half and preferably a greater proportion) of the magnetic flux path between the electrodes thereby to increase the proportion of the magnetic flux path traversing the current path.

CLAIMS

1. A magnetohydrodynamic (MHD) propulsion arrangement comprising means for generating a magnetic flux in a path which extends between opposed electrodes at least one of which extends along a major part of the flux path, said electrodes being of such form and disposition as to provide minimal obstruction to the flow of liquid therebetween transverse to the flux path, the arrangement being such that when the electrodes are immersed in a conductive liquid in the presence of said magnetic flux and an electric current is passed through the conductive liquid between the electrodes, a propulsive force is produced in a direction transverse to the flux path and to the current path.

2. An arrangement according to Claim 1 wherein the opposed electrodes comprise a central localised electrode and an outer electrode surrounding the central electrode.

3. An arrangement according to Claim 2 wherein the central electrode is in the form of a disc and the outer electrode is in the form of an annulus.

4. An arrangement according to Claim 2 wherein the central electrode is in the form of a rod and the outer electrode is in the form of a tube.

5. An arrangement according to Claim 2 wherein the central electrode extends in said direction and the outer electrode also extends in said direction and is of arcuate cross-section transverse to said direction.

6. An arrangement according to any preceding claim, wherein the means for generating a magnetic flux comprises a plurality of solenoids distributed between the electrodes.

7. An arrangement according to Claim 4 or Claim 5, wherein the means for generating a magnetic flux comprises a plurality of solenoids distributed along said flux path, wherein each turn of each solenoid extends along substantially the entire length of the electrodes in said direction.

8. An arrangement according to Claim 4 or Claim 5, wherein the means for generating a magnetic flux comprises a plurality of solenoids distributed along said flux path, each solenoid having spaced apart co-planar sections along the length of the electrodes.

9. An MHD ship propulsion arrangement in accordance with any preceding claim, mounted at the rear end of a ship's hull with said direction aligned with the ship's longitudinal axis and so as to be immersed when the ship is in use.

10. An MHD ship propulsion arrangement according to Claim 5 wherein said outer electrode forms, with the ship's hull and the inner electrode, a duct for the passage of water the reaction from which provides a propulsive force on the ship.

11. An MHD ship propulsion arrangement according to Claim 10, wherein said inner electrode is constituted by the ship's hull.

12. An MHD ship propulsion arrangement according to Claim 10, wherein said inner electrode comprises a conductive surface or surfaces fixed to the ship's hull.

13. A ship incorporating an MHD propulsion arrangement according to any of Claims 9 to 12, wherein said flux path is substantially contained within the ship and the propulsion arrangement.

14. A magnetohydrodynamic propulsion arrangement substantially as hereinbefore described with reference to any of Figures 2, 3 and 4 of the accompanying drawings.

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